***Short Communication***

# Comparison of Two Alternate Methods for Tracking Toe Clearance

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**Abstract**

Analyses of toe clearance during the swing phase of locomotion has often been utilized in determining a subject's propensity to trip while either walking or stepping over an obstacle. In the literature, toe clearance has been studied using a marker on the superior aspect of the second toe (rtoe), a marker on the lateral aspect of the fifth metatarsal head (mth5), or a virtual marker positioned at the anterior tip of the toe (vtoe). The purpose of this study was to compute toe clearance and associated parameters using a fifth metatarsal marker and a virtual toe marker, and compare the results with those of the standard toe marker. Subjects walked on a motorized treadmill at five different speeds while performing a visual acuity task at two separate target distances (ten 60-second trials). The minimum vertical height (TCl) was determined for each stride, along with its point of occurence in the gait cycle, and the angles of the foot and ankle at that time. A regression analysis was performed on the vtoe and mth5 results versus rtoe individually. For all TCl parameters, the mth5 marker did not correlate well with rtoe; the vtoe marker showed better agreement. Most importantly, the mth5 marker predicted a later occurence of TCl than rtoe and vtoe – thereby missing the most dangerous point in swing phase for a trip. From this analysis, the vtoe marker proved to be a better analog to rtoe than mth5, especially for determining a subject's propensity to trip.

## Introduction

Toe trajectory during the swing phase of locomotion has been identified as a precise motor control task involving the joints and muscles on both the stance and swing limbs (Winter, 1992), which gives a global view of the control task (Karst et al., 1999). The study of toe trajectory (more specifically toe clearance) is often utilized in determining the propensity to trip while either walking (Elble et al., 1991; Winter, 1992) or when stepping over an obstacle (Byrne and Prentice, 2003; Mohagheghi et al., 2004).

The standard method for tracking toe motion is to place a marker on the superior aspect of the distal end of the 2nd toe (Karst et al., 1999; Murray and Clarkson, 1966a; Murray et al., 1984; Murray et al., 1985; Winter, 1992). However, others have based their toe trajectory results on a marker positioned on the lateral aspect of the fifth metatarsal head of the foot (Dingwell et al., 1999; Elble et al., 1991; Mills and Barrett, 2001; Osaki et al., 2007). A third method (Begg et al., 2007; Miller et al., 2007; Miller et al., 2006; Moosabhoy and Gard, 2006; Startzell and Cavanagh, 1999) involved computing a "virtual" toe marker – positioned at the tip of the second toe or other point on the anterior sole of the shoe – based on the positions of three other "real" markers on the foot.

The studies using the metatarsal marker or virtual marker all report their results as "toe" clearance. But is either marker a good analogue to the standard toe marker? The purpose of this study was to compute toe clearance using a fifth metatarsal marker and a virtual toe marker, and compare their results with those of the standard toe marker.

## Methods and Materials

This analysis utilized data collected from a previous study that determined the effects of treadmill walking speed and visual target distance on toe trajectory parameters (Miller et al., 2007; Miller et al., 2006). The main features of the protocol were as follows.

Twelve subjects (6M, 6F; height = 172.0 ± 9.74 cm.; age = 33 ± 8.0 years; weight = 71.1 ± 14.94 kg.) gave informed consent and participated in this study. This institution's Committee for the Protection of Human Subjects reviewed and approved this protocol.

Subjects wore lab-supplied shoes (Converse, North Andover, MA) with footswitches (Motion Lab Systems, Baton Rouge, LA), sampled at 1000 Hz, affixed to the heel and toe areas of the soles. A six-camera Motion Analysis system (Santa Rosa, CA) recorded 3D marker positions of the right leg at 60 Hz. On the right shoe specifically, markers were placed at: the distal end of the 2nd toe (rtoe), the fifth metatarsal head (mth5), the lateral surface at the calcaneus, and the top surface at the navicular bone (Figure 1). The virtual marker (vtoe) was computed during post-processing based on the positions of the mth5, calcaneal, and navicular markers. Its position was set at the distal end of the shoe at the second toe, at the same relative height on the shoe as mth5. In other words, when the foot was flat on the walking surface, $vtoe_z = mth5_z$ (see Figure 1). The vtoe marker represented the point on the shoe that would likely contact the walking surface during a trip. The vertical positions of rtoe, vtoe and mth5 during walking trials were reported relative to their respective heights during a quiet-standing trial, which was recorded before the walking trials.

Subjects completed ten 60-second walking trials while walking on a motorized treadmill (Gaitway, Kistler Instrument Corp., Amherst, NY) and performing a dynamic visual acuity task (Peters and Bloomberg, 2005).

Footswitch data were used to determine heel strike events and for the time normalization of the motion data. Euler angles for the leg segments and joints were computed from the marker positions. Only the ankle and foot flexion angles of the swing leg are reported, since they were determined to be the main angles that affect toe clearance (TCl) measures (Miller et al., 2007; Miller et al., 2006; Moosabhoy and Gard, 2006).

The TCl during swing phase was computed for each stride, along with the point in the gait cycle when TCl occurred (%GC), and the ankle and foot flex/extension angles at the TCl event. Individual stride results were averaged over the trial before statistical analysis.

A random-effects regression analysis was performed on each vtoe and mth5 alternative measurement averaged over strides versus the corresponding rtoe (the standard) average. If, on average, a given alternative measurement was reflecting the same gait characteristics as rtoe, then the intercept of the regression line would be zero and the slope would be equal to one. A further indicator of consistency of each alternative measurement with respect to the population of subjects is the standard deviation of the random subject-specific intercepts, which was also estimated in the random-effects regression analysis.

**Results**

Table 1 shows the estimated slopes, intercepts and standard deviation of the intercepts across subjects for the two comparisons. The mth5 marker did not correlate well with rtoe for any of the TCl parameters, as shown by greatly diminished, nearly flat, slopes. The TCl results for vtoe vs. rtoe showed better agreement, especially for minimum height, though the large intercept (29.9%GC) for the timing correlation was surprising. Subject-to-subject SDs were consistently lower for vtoe vs. rtoe regressions than mth5 vs. rtoe.

The values of minimum mth5 marker height (mth5-TCl) were not close to zero (relative to its standing height) and were greater than the associated values of rtoe (rtoe-TCl) and vtoe (vtoe-TCl) (Figure 2a). The vtoe-TCl events occurred slightly later in the gait cycle than rtoe-TCl (Figure 2b), however the mth5-TCl events occurred much later than those of the other markers. The swing foot at mth5-TCl was nearly parallel to the walking surface (foot angle < 10°) (Figure 2c), where the foot was in flexion at the rtoe-TCl and vtoe-TCl events. The ankle angles at mth5-TCl and vtoe-TCl did not correlate well with the ankle angle at rtoe-TCl (Figure 2d and Table 1).

**Discussion**

*Trip assessment*: Winter (1992) described the most dangerous point during swing phase as when the swing leg just passes the stance leg and the height of rtoe is at its minimum. Trip recovery would require rapid swing leg extension to arrest the body’s forward momentum and ankle dorsiflexion to get the foot’s plantar-surface parallel to the floor. This “danger point” would be missed if the mth5 marker was used for determining

tripping potential, because the minimum height of mth5 occurred much later in the gait cycle than that of rtoe (Figure 2b). By that time, the lower body was in a better position for recovery: the swing leg was extended anterior to the stance leg, and the swing foot's plantar-surface was nearly parallel to the walking surface (Figure 2c). On the other hand, the timing of the minimum height of vtoe was much closer to the rtoe-TCl event. The lower body was still in a precarious position for a trip, in that the foot was still in flexion, and the vtoe marker's height was *below* its standing height (Figure 2a). It would seem therefore that an assessment of tripping potential should be based on the minimum height of rtoe or vtoe, rather than mth5.

*Marker advantages/disadvantages*: The position of the mth5 marker relative to the markers on the rear foot is not affected by flexion at the midfoot between heel-off and toe-off, hence it can be used for calculating foot orientation and local-coordinate axes during locomotion. The rtoe marker, on the other hand, moves relative to the rear-foot markers during midfoot flexion in late stance (Figure 3). Erroneous foot orientation values would result if angle calculations included rtoe. Therefore its use is limited to tracking toe motion or helping determine the midline of the foot during a standing trial.

While the rtoe marker is the most common method for tracking toe trajectory, it does not necessarily designate the actual point that would contact the walking surface during a stumble. The vtoe marker, on the other hand, can be located anywhere on the anterior edge or sole of the shoe that is thought to contact the floor during tripping (Begg et al., 2007; Moosabhoy and Gard, 2006; Startzell and Cavanagh, 1999). But computing the 3-D location of vtoe depends on position data from three *other* markers on the foot. If

data from any of the three foot markers are lost or are of poor quality, the vtoe position can not be determined accurately.

Despite this potential limitation, the vtoe marker proved to be a better analog to rtoe than mth5, especially when assessing tripping potential. Its TCl event occurred near the "danger point" of swing phase, and the marker can be located to the exact contact-point of the shoe that would cause a stumble.

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## Figures

**Figure 1** Photo showing the marker positions on the shoe: the top surface at the distal end of the 2nd toe (rtoe), the lateral surface at the fifth metatarsal head (mth5), the lateral surface at the calcaneus, and the top surface at the navicular bone. The calculated position of the virtual toe marker is depicted by the white circle with the "V." Note that during quiet stance, vtoe and mth5 are at the same vertical height.

**Figure 2** Graphs of: (a) the toe clearance, or TCl; (b) %GC of TCl, (c) foot flexion angle at the point of TCl, (d) and ankle flexion angle at the point of TCl for mth5 and vtoe versus that of the rtoe marker.

**Figure 3** Photos showing the change in the relative position of the rtoe marker relative to the other foot markers during (a) quiet standing and (b) late-stance phase. Note the significant change in distance between rtoe and the navicular and calcaneal markers. Also note the increase in the angle between the rtoe-calcaneus and mth5-calcaneus vectors.

**Figure 1**

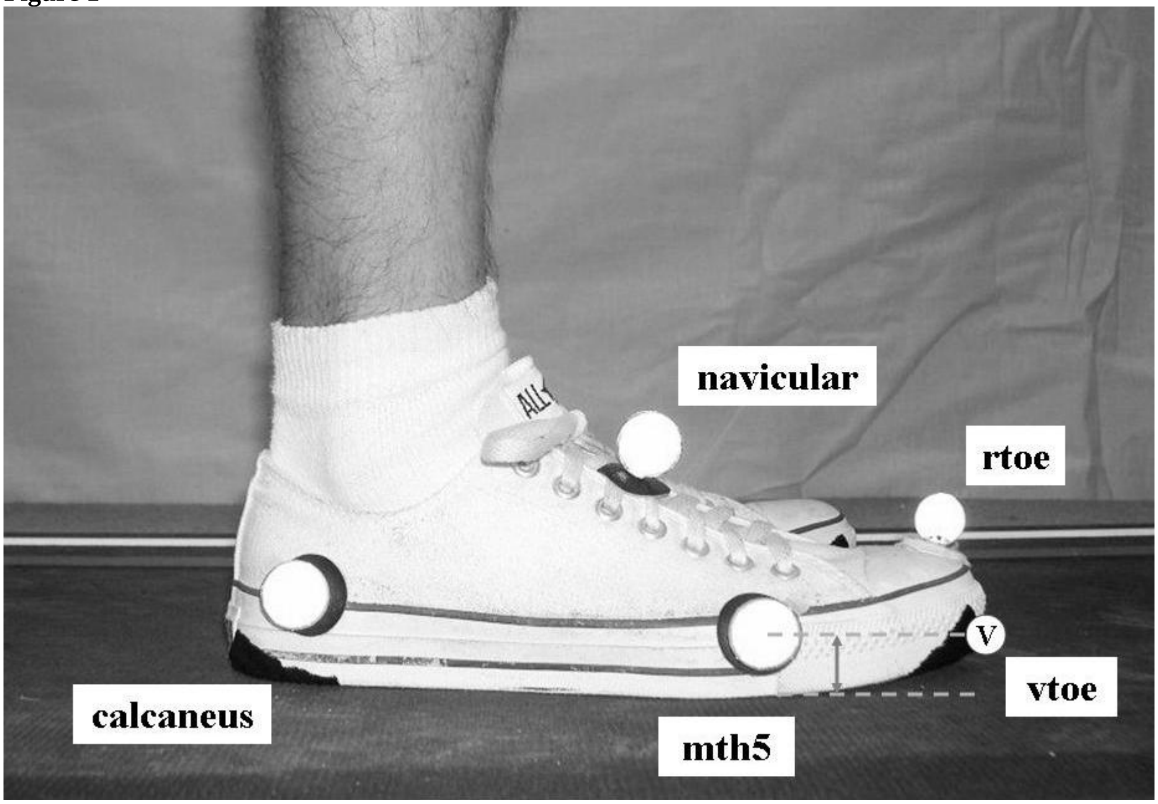


**Figure 2**

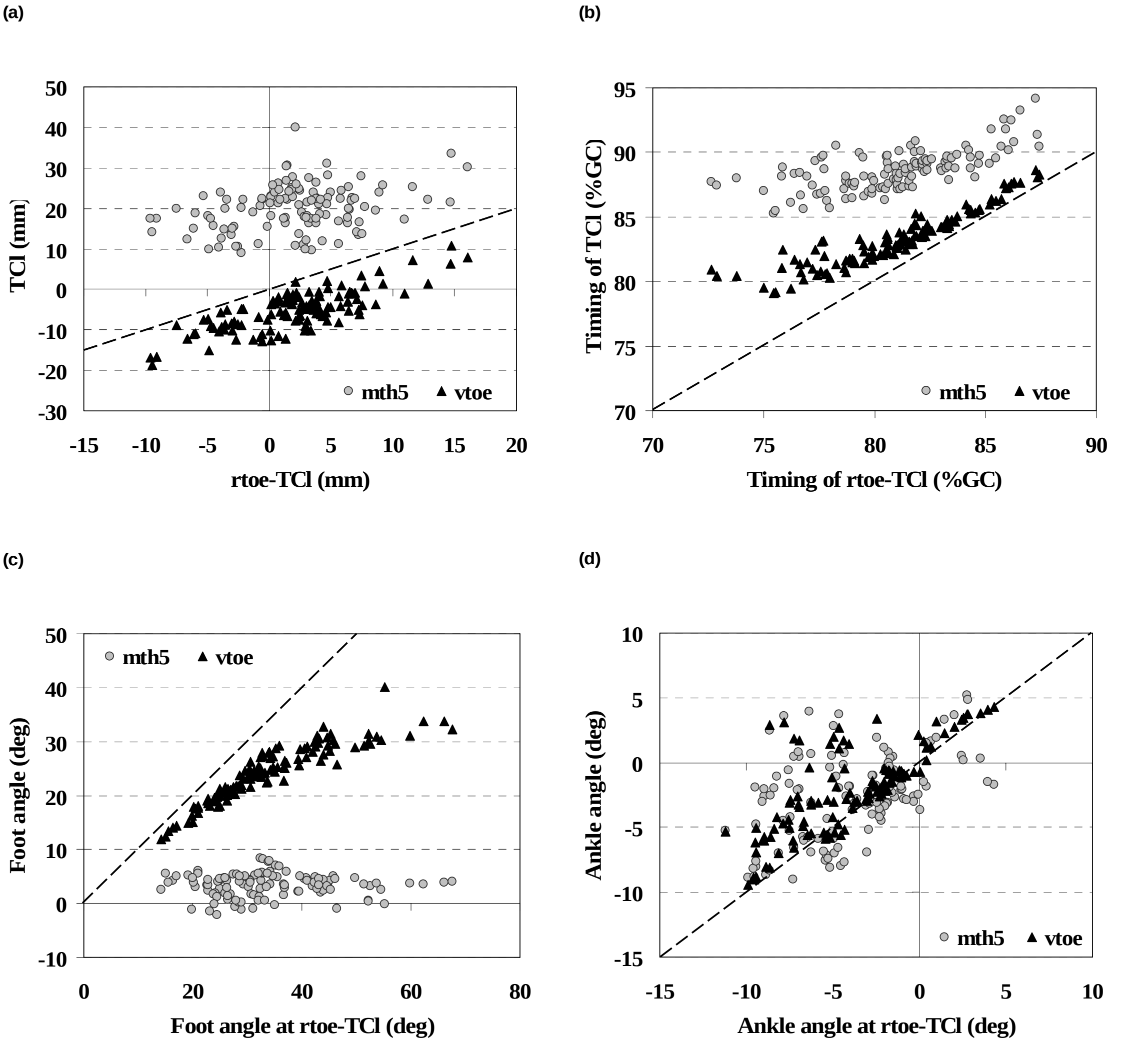
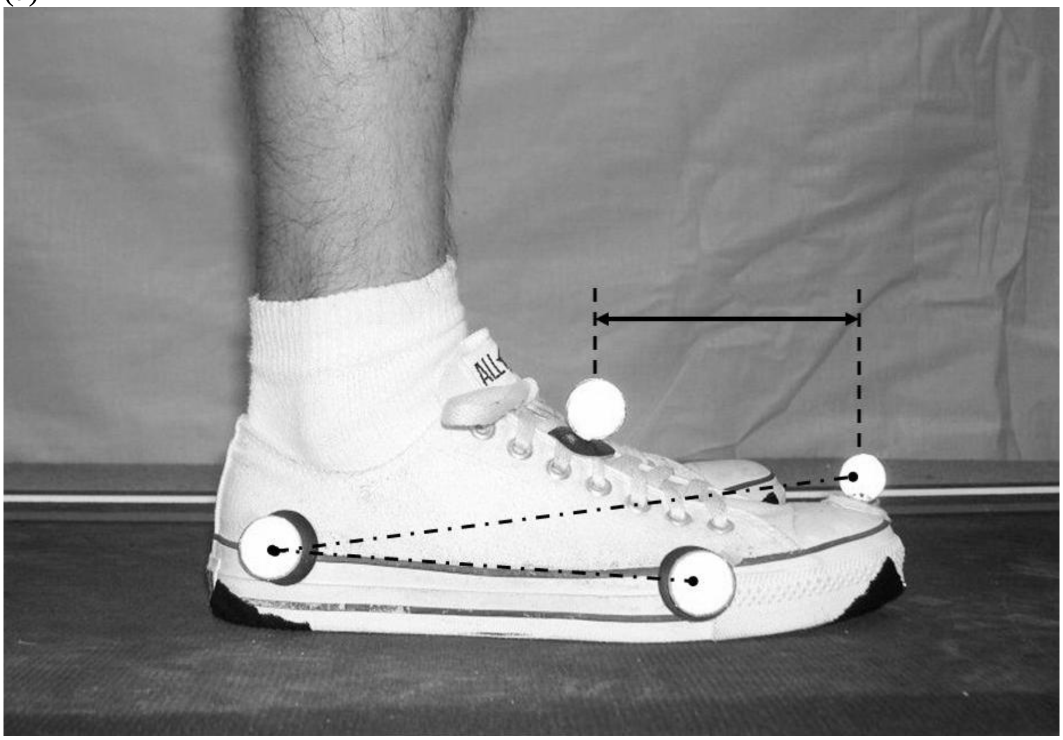

(a)
TCl (mm)
rtoe-TCl (mm)
mth5
vtoe
(b)
Timing of TCl (%GC)
Timing of rtoe-TCl (%GC)
mth5
vtoe
(c)
Foot angle (deg)
Foot angle at rtoe-TCl (deg)
mth5
vtoe
(d)
Ankle angle (deg)
Ankle angle at rtoe-TCl (deg)
mth5
vtoe

**Figure 3**

(a)



(b)

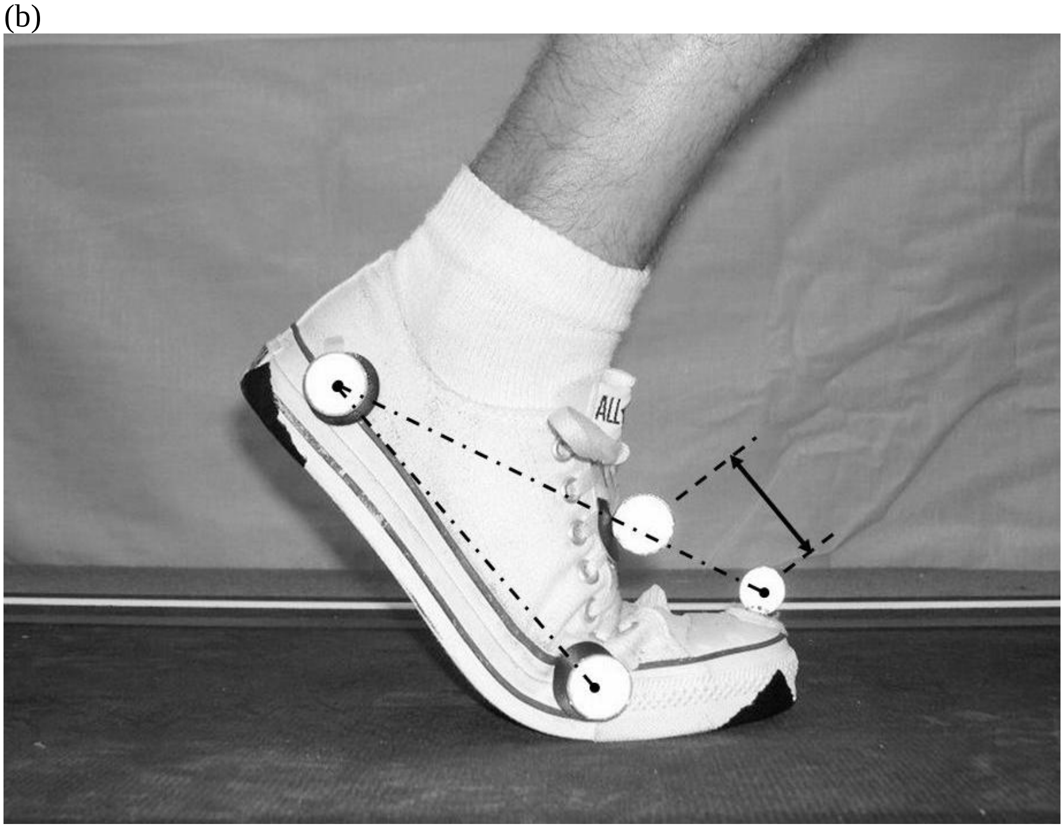


**Table 1:** Regression line fit results for TCl parameters based on vtoe vs. rtoe, and mth5 vs. rtoe. $SD_{sub}(b)$ is the standard deviation of subject-to-subject intercepts.

| | | Slope (m) | Intercept (b) | $SD_{sub}$ |
|---|---|---|---|---|
| **Height (mm)** | **vtoe** | 0.801 | -6.8 | 3.16 |
| | **mth5** | -0.004 | 20.1 | 4.08 |
| **Timing (%GC)** | **vtoe** | 0.659 | 29.9 | 0.66 |
| | **mth5** | 0.391 | 57.0 | 0.96 |
| **Foot Angle (deg)** | **vtoe** | 0.490 | 7.6 | 1.64 |
| | **mth5** | 0.018 | 2.8 | 2.13 |
| **Ankle Angle (deg)** | **vtoe** | 0.354 | -0.7 | 1.93 |
| | **mth5** | -0.039 | -2.8 | 2.11 |